Test of CP-invariance of the Higgs boson in vector-boson fusion production and its decay into four leptons

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Overview

- CP violation is one of three ingredients required for the observed Baryon Asymmetry of the Universe (BAU)
- The observed CP violation, first in kaon system and then extensively in b- and c-mesons, can be explained by the CP-violating complex phase of the CKM matrix
- However, this complex phase is not sufficient to explain BAU
  - => so other sources of CP-violation are required
- Two possibilities are the neutrino sector, and the Higgs sector
  - Here we explore the H -> ZZ* -> 4l (l = e, μ) channel in both VBF production and the 4l decay
  - Other Higgs searches are/have been performed in the Higgs - fermion sector

Overview of the H->ZZ*->4l CP-violation search

- This measurement uses CP-odd optimal observables (OO)
  - Moriond EW 2023, arxiv:2304.09612, submitted to JHEP, CERN News
  - Largely based on the work in the thesis of Antoine Laudrain 2019
- Full Run 2 data set in ATLAS, 139 fb^{-1}, with about 200 H->ZZ*->4l decays including about 10 vector boson fusion (VBF) events expected
- The optimal observables are built from SMEFT matrix elements (MadGraph LO)
  - Three dim-6 CP-odd operators contribute with different sensitivity to VBF production and H4l decay
- Two types of measurements: OO distributions are used both
  - to directly constrain CP-odd couplings, and
  - unfolded to fiducial phase space to allow model reinterpretation
- CP-odd search is based on shape-only asymmetries, ignoring x-sec changes
- Also include inclusive x-sec in VBF fiducial phase space

Methodology

- SMEFT Lagrangian (dim-6 operators):

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)}$$

- Two sets of three CP-odd couplings - Lagrangian before and after EW symmetry breaking
  - Warsaw and Higgs bases
- Warsaw basis is the "accepted" basis for measurement combinations
- Higgs basis has couplings more closely aligned with measurement sensitivity, i.e. for VBF prod or H4l decay
- Provide results for both
  - One basis linearly transforms into the other
- For comparison with an earlier H$\tau\tau$ measurement:
  - $\tilde{d}$ where $c_{H\widetilde{W}} = c_{H\widetilde{B}} = \frac{\Lambda^2}{v^2}\tilde{d},$

HVV coupling

Operator	Structure	Coupling
	Warsaw Basis	
$O_{\Phi\tilde{W}}$	$\Phi^\dagger\Phi\tilde{W}^I_{\mu\nu}W^{\mu\nu I}$	$c_{H\widetilde{W}}$
$O_{\Phi\tilde{W}B}$	$\Phi^\dagger\tau^I\Phi\tilde{W}^I_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{W}B}$
$O_{\Phi\tilde{B}}$	$\Phi^\dagger\Phi\tilde{B}_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{B}}$
	Higgs Basis	or
$O_{hZ\tilde{Z}}$	$hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$	$\tilde{c}_{zz}$
$O_{hZ\tilde{A}}$	$hZ_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{z\gamma}$
$O_{hA\tilde{A}}$	$hA_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{\gamma\gamma}$

Methodology (2)

- Cross section is matrix element squared:

$$|\mathcal{M}|^2 = \left|\mathcal{M}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{M}_{\mathrm{BSM},i}\right|^2$$

$$= |\mathcal{M}_{\mathrm{SM}}|^2 + 2\sum_i \frac{c_i}{\Lambda^2}\Re\left(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{BSM},i}\right) + \sum_i\sum_j \frac{c_i c_j}{\Lambda^4}\Re\left(\mathcal{M}^*_{\mathrm{BSM},i}\mathcal{M}_{\mathrm{BSM},j}\right)$$

SM — interference term — quadratic term

CP: even — odd — even

- OO for each coupling is the interference term normalized by SM

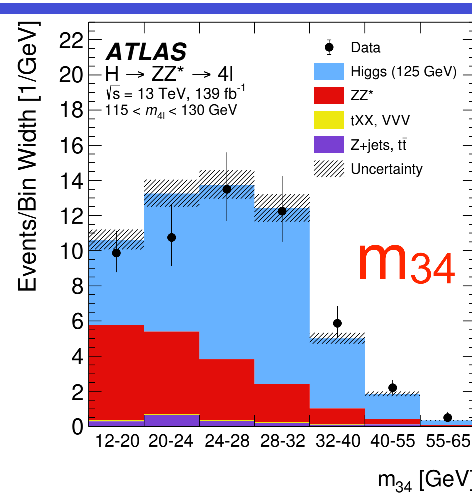
$$OO = \frac{2\Re\left(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{BSM}}\right)}{|\mathcal{M}_{\mathrm{SM}}|^2}$$

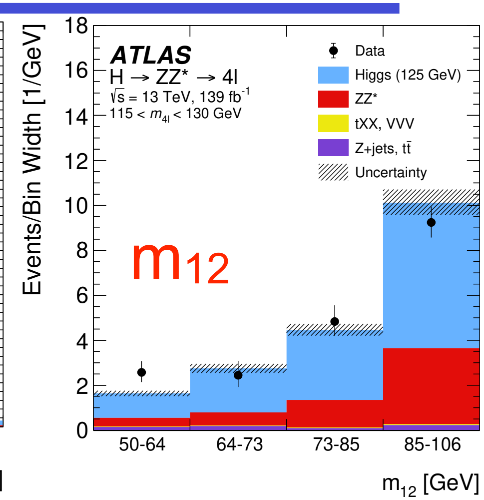
LO MEs calculated with MadGraph for OO

- Samples are simulated with SMEFT-sim (MadGraph LO + Pythia) in 3-d coupling space
  - Using interpolation (morphing) to evaluate cross section at any point
  - Morphing includes linear and quadratic terms, but x-sec is normalized to SM

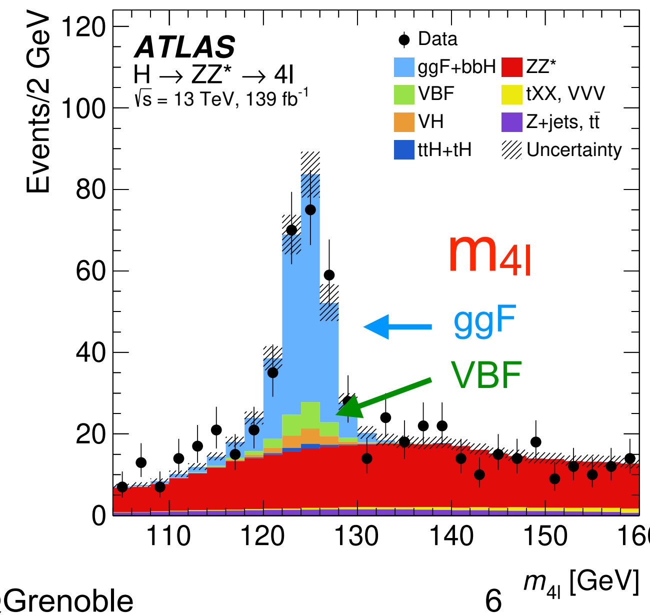
H -> ZZ* -> 4l reconstruction and selection

- **Triggers**: 1,2,3-lepton triggers
  - 98% eff
- "Loose" lepton ID,
  - $p_T > 5$ (7) GeV for μ (e)



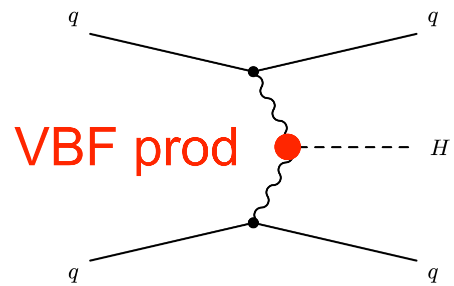


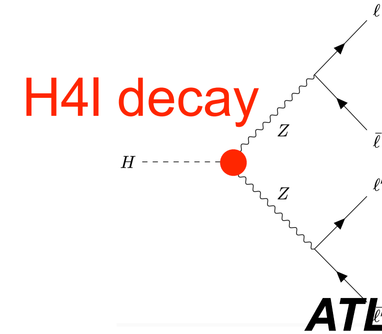
- **Backgrounds**:
  - ZZ* non-resonant (side-band fit)
  - reducible Z+jet, tt (data-driven)
    - reduced with isolation + d_0 cuts
- Four channels: 4μ, 2e2μ, 2μ2e, 4e
  - Leading pair ~onshell Z, subleading pair ~offshell Z

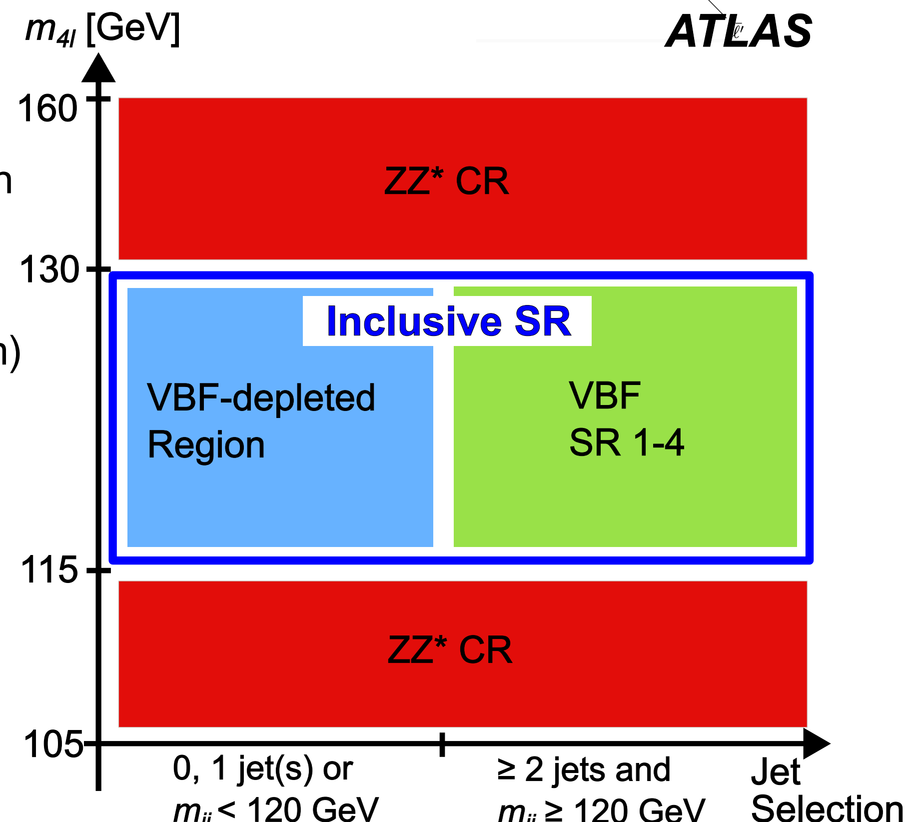


Analysis Overview

- Direct measurement:
  - Decay-only OO fit:
    - all events, m_{4l} in 115 - 130 GeV
    - ZZ* normalized in mass side-bands
  - VBF Production-only OO fit:
    - 2-jet events with m_{jj} > 120 GeV and m_{4l} in 115 - 130 GeV
    - Separate VBF from ggF with neural network - SR 1-4 bins (VBF floating norm)
    - ggF normalized by VBF-depleted region, as ZZ* as above
  - Combined OO fit:
    - VBF OO fit is same
    - Decay OO fit uses only VBF-depleted events



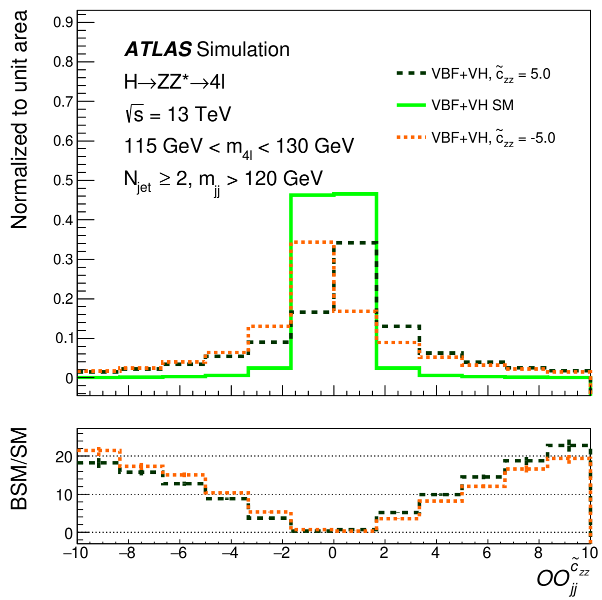




Optimal observable distributions

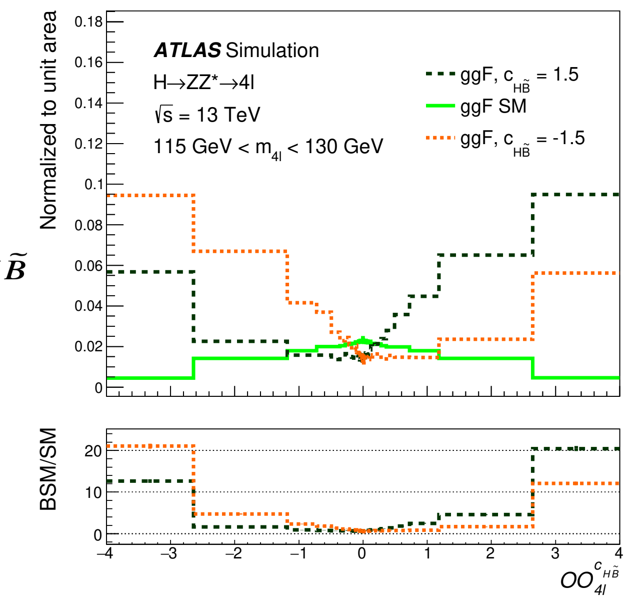
OO for VBF production - equal-sized binning

$OO_{jj}^{\tilde{c}_{zz}}$



OO for decay - equally-populated binning

$OO_{4\ell}^{c_{H\tilde{B}}}$



- SM OO distribution is symmetric (green)
- Adding CP-odd coupling shows clear asymmetry depending on sign of coupling (Mean ≠ 0)
- Right plot with equally-populated bins shows important effect of the distribution tails
  - Equal population binning is used in the fits of this analysis
    - done with mix of SM + BSM expected distributions

CP asymmetries

- For VBF production and H4l decay, the CP asymmetry is largely embedded in:
  - $\Delta\varphi_{jj}$ - the η-ordered angular separation of the di-jet system for VBF production, which is CP-asymmetric itself, and
  - m_{12} and m_{34} - the masses of the leading and subleading di-lepton pairs of the Higgs decay, which are not directly CP-asymmetric themselves
- These Optimal Observables capture more information in the Matrix Elements, and are CP-odd asymmetric
  - E.g. we have seen significantly better limits for VBF using OO rather than $\Delta\varphi_{jj}$

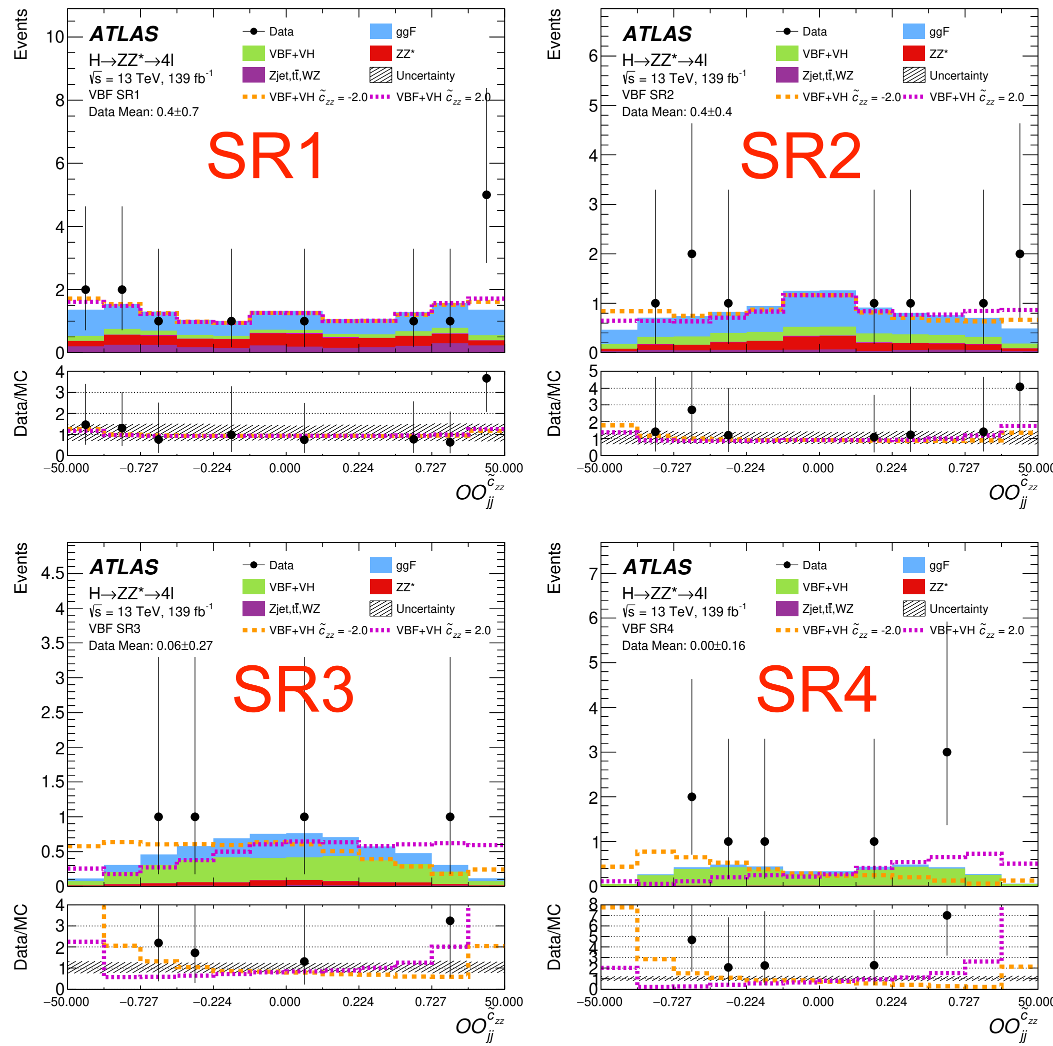
Fiducial analysis

- Unfold the optimal observable distributions
- Measure fiducial cross section in enhanced VBF region:
  - m_{jj} > 400 GeV and $|\eta_{jj}|$ > 3.0
  - Two measurements:
    - Fid x-sec in this region (mix of ggF, VBF, VH, ttH): VBF purity ~59%
    - Fid x-sec including ggF-estimate as background (side-band norm, shape from MC): purity ~95%
      - But this is more model dependent
- Completes the fiducial differential distributions of H4l fiducial analysis

Leptons and jets	
Leptons	$p_T > 5$ GeV, $\|\eta\| < 2.7$
Jets	$p_T > 30$ GeV, $\|y\| < 4.4$
Lepton selection and pairing	
Lepton kinematics	$p_T > 20, 15, 10$ GeV
Leading pair (m_{12})	SFOC lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Subleading pair (m_{34})	Remaining SFOC lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Event selection (at most one quadruplet per event)	
Mass requirements	50 GeV $< m_{12} <$ 106 GeV and $m_{\text{threshold}} < m_{34} <$ 115 GeV
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.1$
Lepton/Jet separation	$\Delta R(\ell_i, \text{jet}) > 0.1$
J/ψ veto	$m(\ell_i, \ell_j) > 5$ GeV for all SFOC lepton pairs
Mass window	105 GeV $< m_{4\ell} <$ 160 GeV
If an extra lepton with $p_T > 12$ GeV is found, the quadruplet with the largest matrix element value is kept	

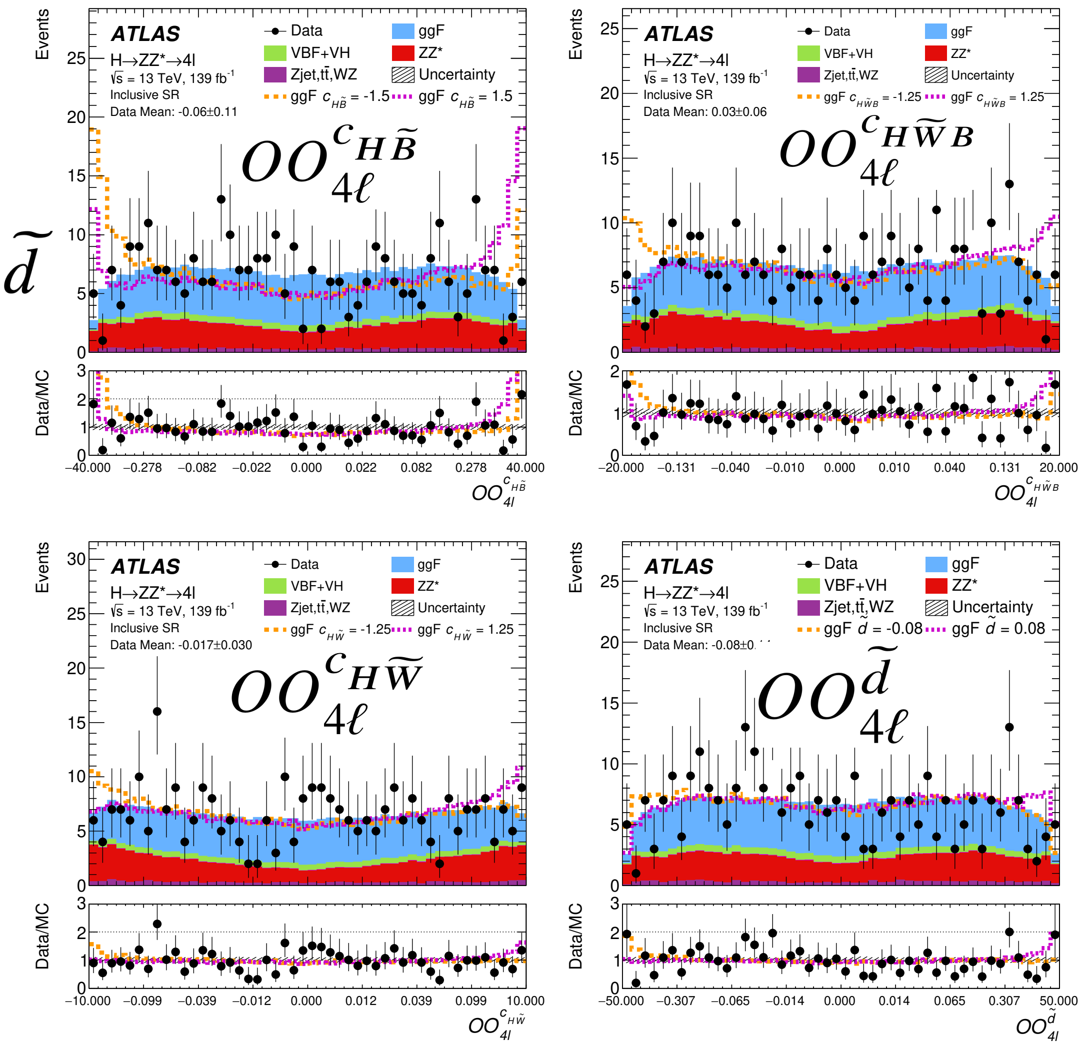
Results: VBF prod $OO^{\tilde{c}_{zz}}_{jj}$ data distributions

- data compared to expected distributions
  - events with 2 jets, m_{jj} > 120 GeV
    - 35 events expected
  - both SM and potential BSM expectations shown
  - SR4: 8 events seen, 4.1 ± 0.5 expected
  - 12 bins for VBF fit
  - fluctuation in positive SR1 affects likelihood scan



Results: decay-only OO data distributions

- Optimal observable distributions for:
  - $c_{H\widetilde{B}}, c_{H\widetilde{W}B}, c_{H\widetilde{W}}, \tilde{d}$
- BSM CP-odd clearly peaks in tails
- 48 bins for decay fit
  - each bin here is plotted with equal width
- Data in good agreement with SM

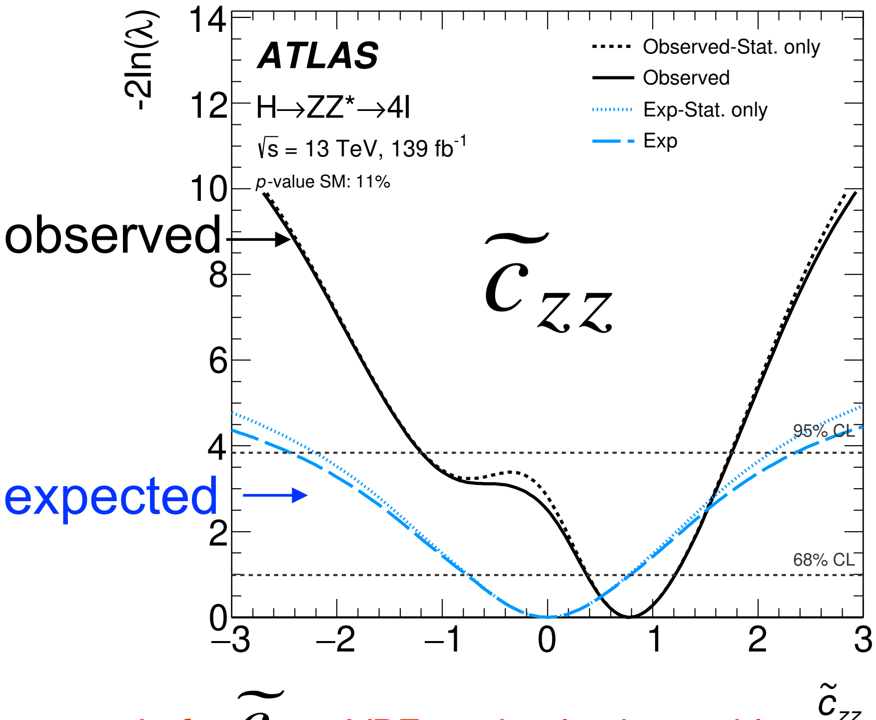


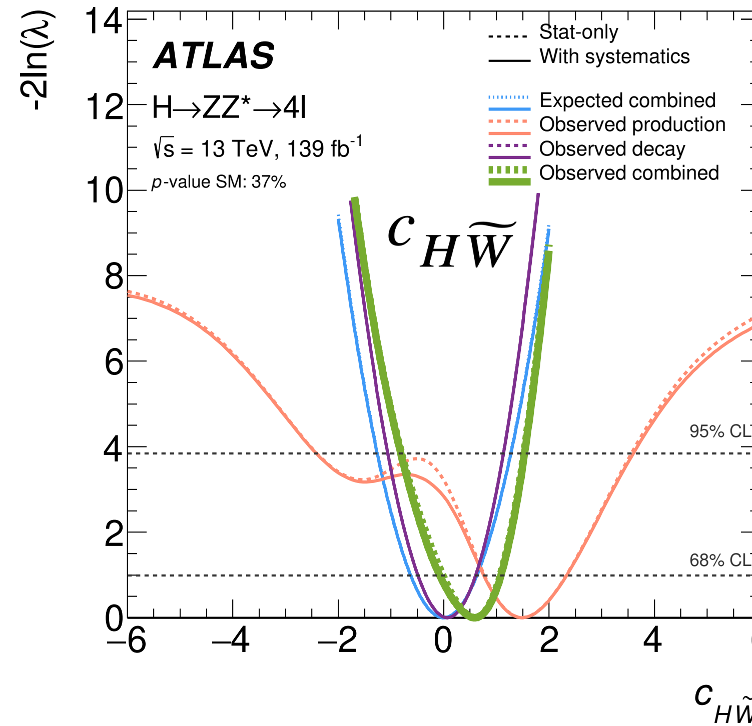
Expected sensitivity - 95% CLs

- Table shows relative sensitivity for prod / decay / combined
  - Recall: ~200 events inclusively, ~10 VBF events
  - Note: combined fit keeps ~90% of all events for decay fit (missing ggF 2 jet events)

	EFT coupling	Expected 95% CL		
		production-only	decay-only	combined
Warsaw basis	$c_{H\tilde{B}}$	–	±0.37	–
	$c_{H\tilde{W}B}$	–	±0.72	–
	$c_{H\tilde{W}}$	±4.8	±1.34	±1.27
Higgs basis	$\tilde{d}$	±0.63	±0.018	±0.019
	$\tilde{c}_{zz}$	±2.4	–	–
	$\tilde{c}_{z\gamma}$	±6.6	±0.76	±0.80
	$\tilde{c}_{\gamma\gamma}$	–	±0.76	–

Likelihood scan for VBF prod and combined

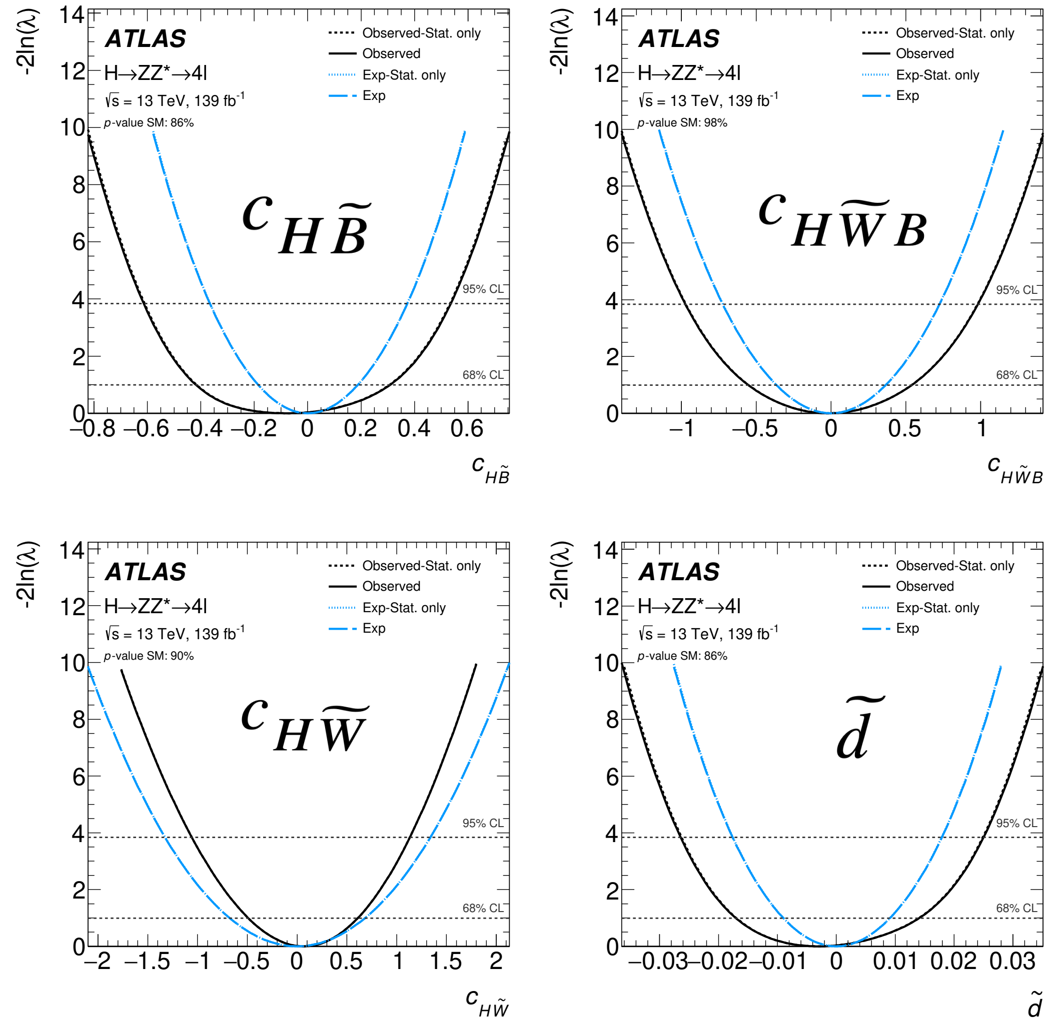




- Left: $\widetilde{c}_{ZZ}$ VBF prod-only observable scan
  - offset due to fluctuation in SR1 - also origin of larger syst effect near $\widetilde{c}_{ZZ}$ = 0 from parton shower moving ggF 2 jet events into SR
- Right: $c_{H\widetilde{W}}$ VBF prod-only (orange), decay-only (purple), and combined (green) observable scans
- dashed line - stat-only, solid line - with systematics

Decay-only observable likelihood scans

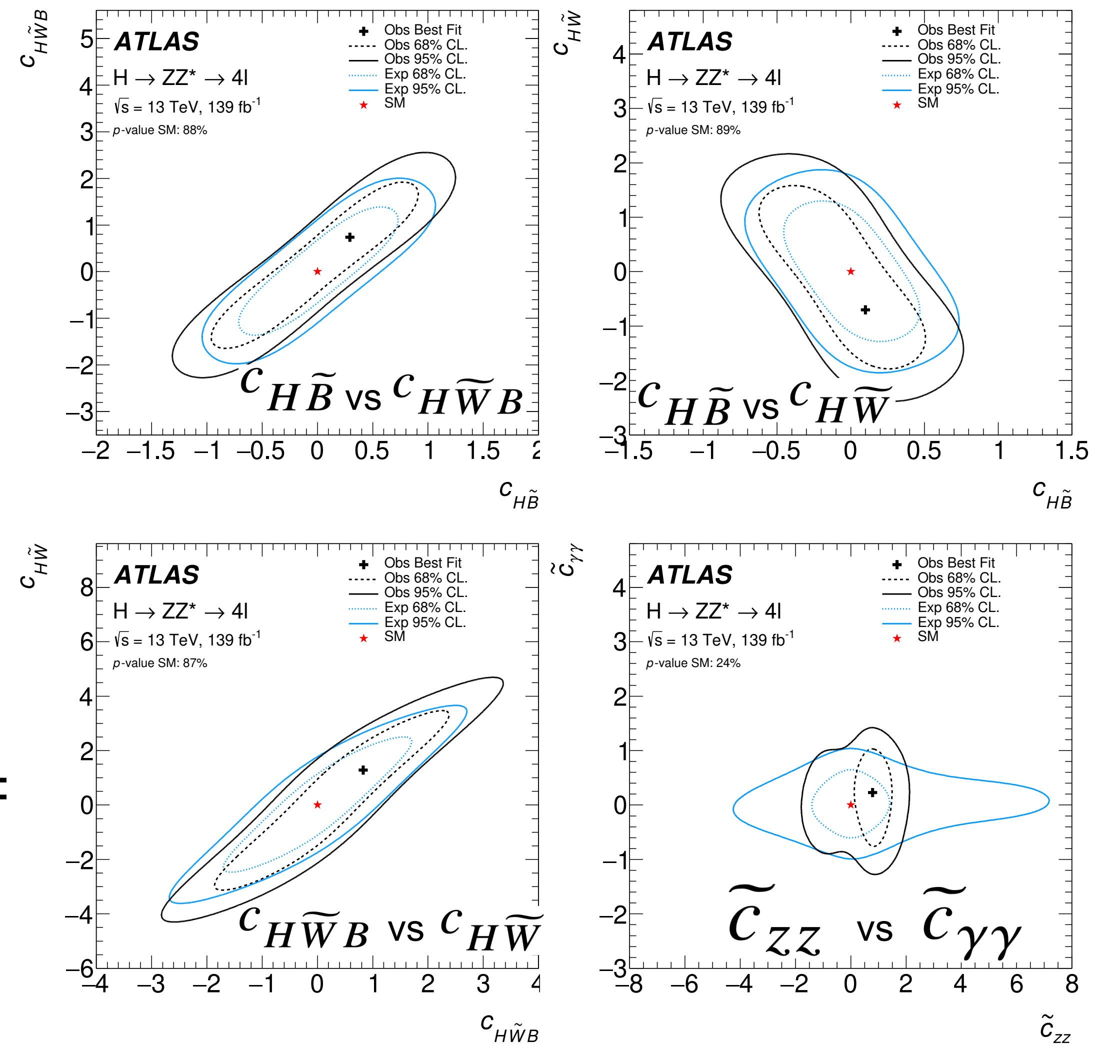
- Systematics are negligible
- Slightly worse (better) observed limits for $c_{H\tilde{B}}$, $c_{H\tilde{W}B}$, and $\tilde{d}$ ($c_{H\tilde{W}}$)
  - due to small excesses in tails (deficit in center)
- Good agreement with SM!



Likelihood scans in 2-d

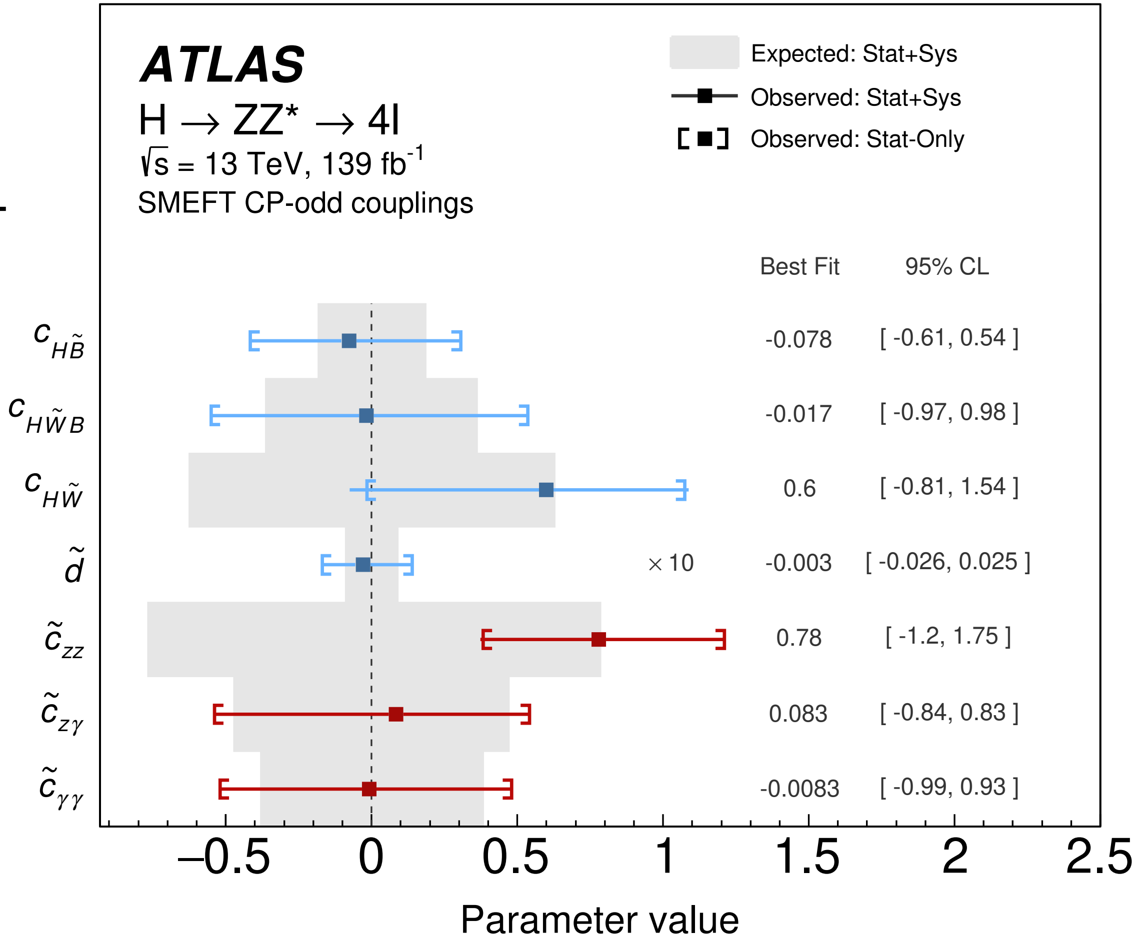
- Decay-only observable scans for all pairing of 3 Warsaw couplings:
  - $c_{H\widetilde{B}}$ vs $c_{H\widetilde{W}B}$,
  - $c_{H\widetilde{B}}$ vs $c_{H\widetilde{W}}$, and
  - $c_{H\widetilde{W}B}$ vs $c_{H\widetilde{W}}$

- For Higgs basis couplings, observable scans for VBF prod for $\widetilde{c}_{ZZ}$ and decay-only for $\widetilde{c}_{\gamma\gamma}$



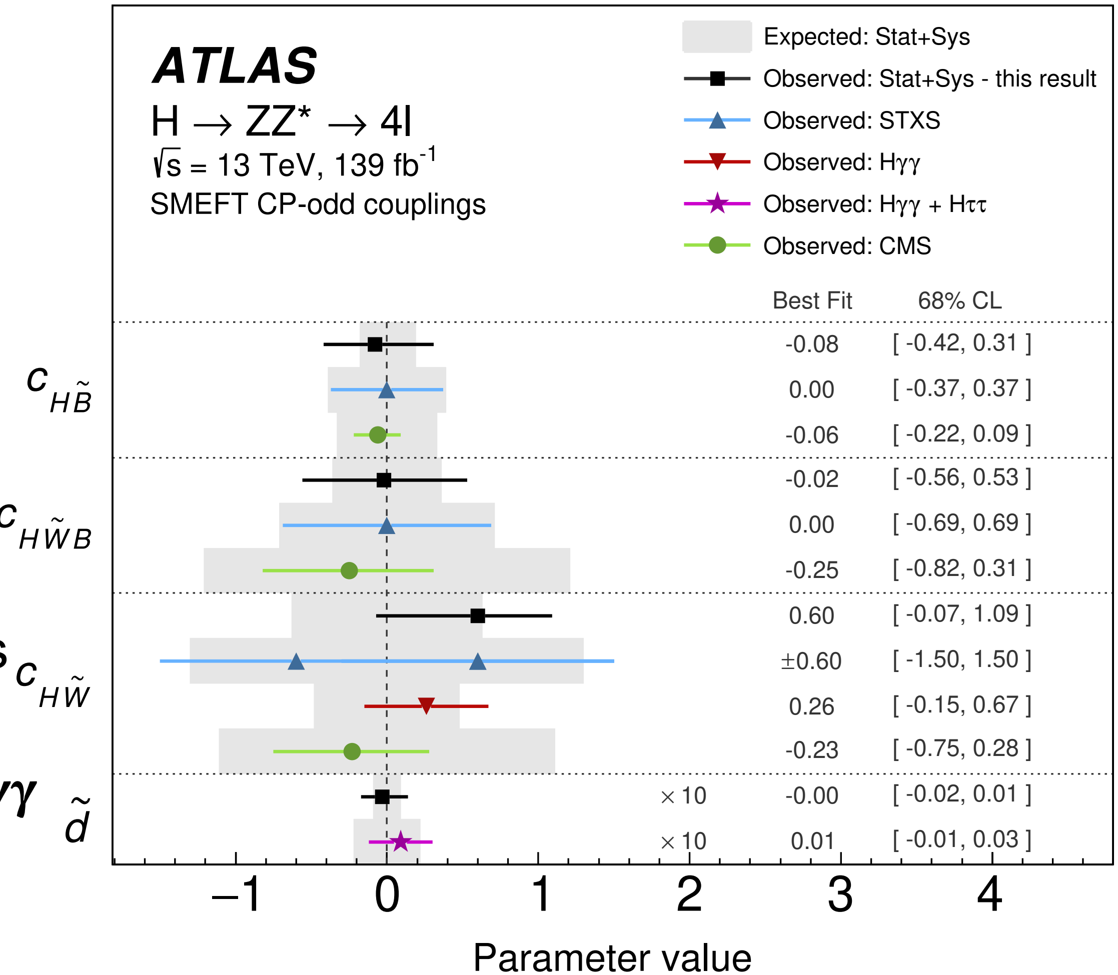
Summary of direct results

- Observables scans:
  - Expected - gray bands
  - Observed data points + 68% CL uncertainties
    - 95% CL also given
  - $\widetilde{c}_{ZZ}$ - prod-only
  - $c_{H\widetilde{W}}$ combined
  - others - decay-only
- All results in good agreement with SM



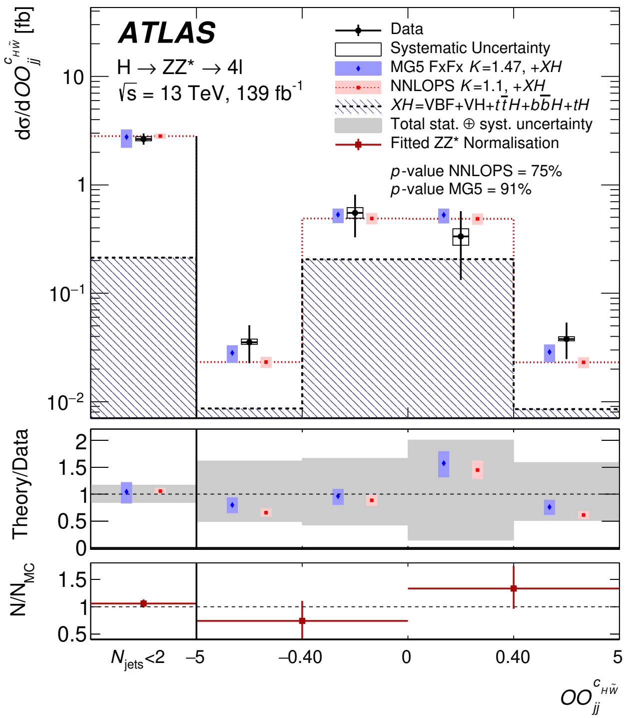
Comparison with other measurements

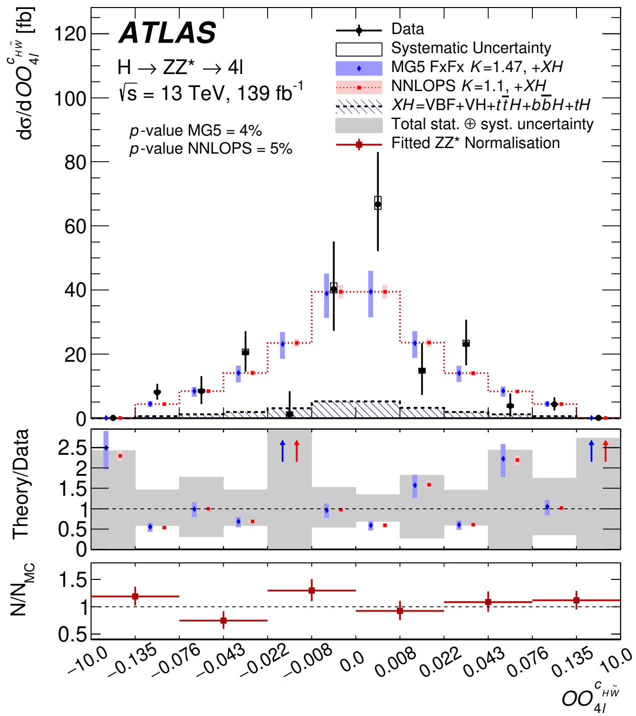
- Comparison with:
  - H4l STXS - x-sec only, not CP-odd specific
  - ATLAS CP-odd H$\gamma\gamma$ VBF
    - combined with H$\tau\tau$ for $\tilde{d}$
  - CMS H4l CP-odd
- All agree with SM
- Present measurement has best expected sensitivity (gray bands) except for H$\gamma\gamma$ VBF for $c_{H\widetilde{W}}$
  - Due to higher VBF stats



Differential optimal observables distributions

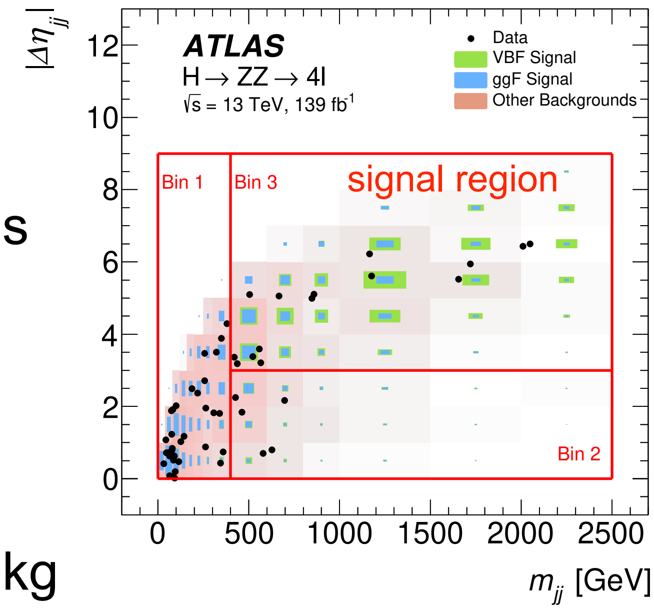
- Distributions for production $OO_{jj}^{c_{H\widetilde{W}}}$, and decay $OO_{4\ell}^{c_{H\widetilde{W}}}$
  - Fewer bins than for direct due to unfolding bin optimization
  - Other observable differential distributions available





VBF-enriched fiducial cross-section

- VBF-enriched region defined as
  - SR: m_{jj} > 400 GeV and $|\eta_{jj}|$ > 3.0 (bin 3)
  - Background normalized from side-bands
- x-sec provided for
  - all productions modes in SR
  - only VBF, VH, ttH with ggF treated as bkg



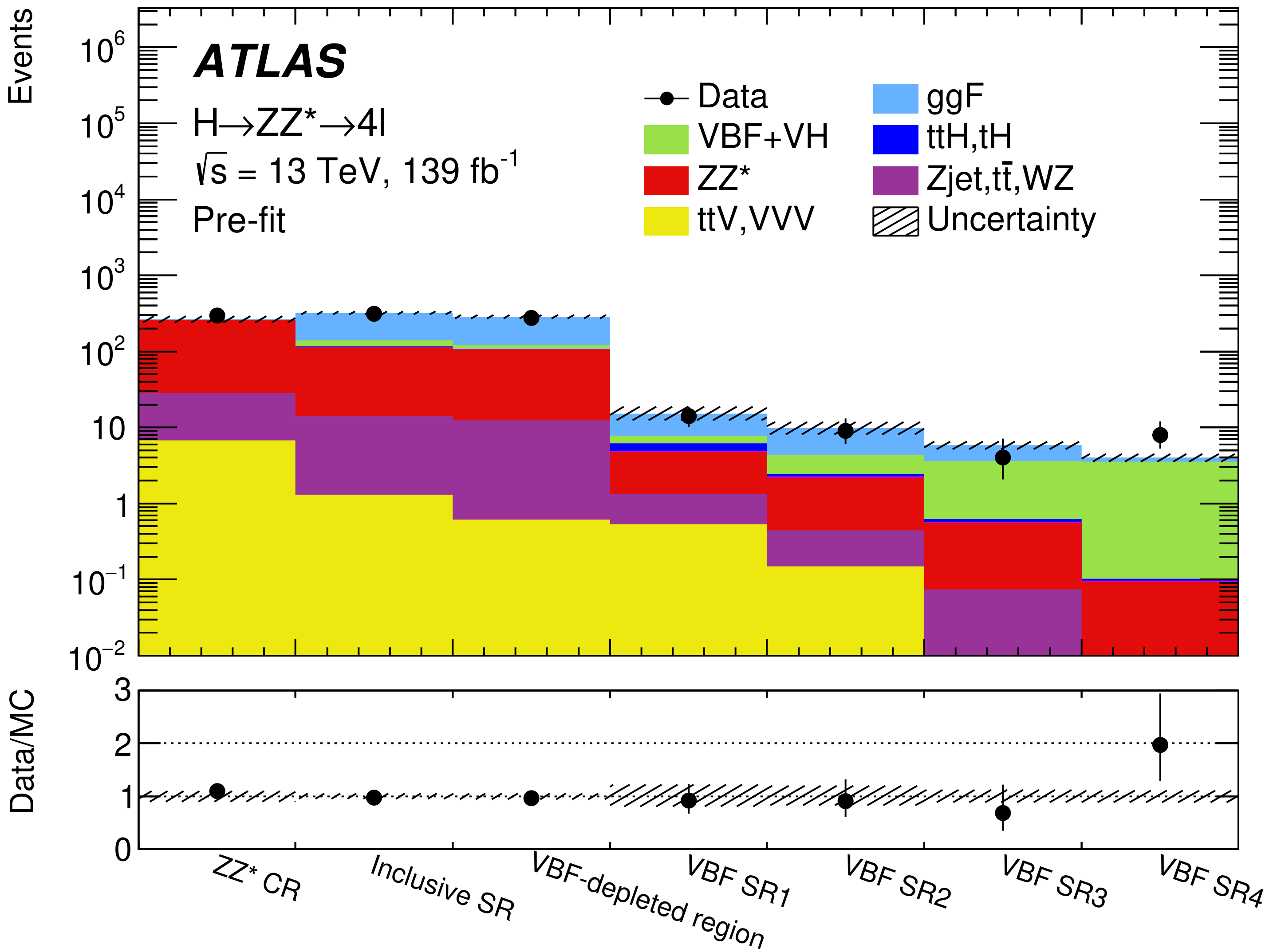
VBF–enriched region	Signal for cross-section estimates	Purity of VBF signal	Expected cross-section [fb]	Observed cross-section [fb]
$N_{\text{jets}} \geq 2,\ m_{jj} \geq 400$ GeV	All production modes	59 %	$0.134^{+0.065}_{-0.053}{}^{+0.014}_{-0.012}$	$0.215^{+0.075}_{-0.063}{}^{+0.016}_{-0.013}$
$\|\Delta\eta_{jj}\| \geq 3.0$	VBF $+VH$ $+ttH$	95 %	$0.088^{+0.063}_{-0.053}{}^{+0.017}_{-0.020}$	$0.172^{+0.072}_{-0.062}{}^{+0.016}_{-0.018}$

Summary

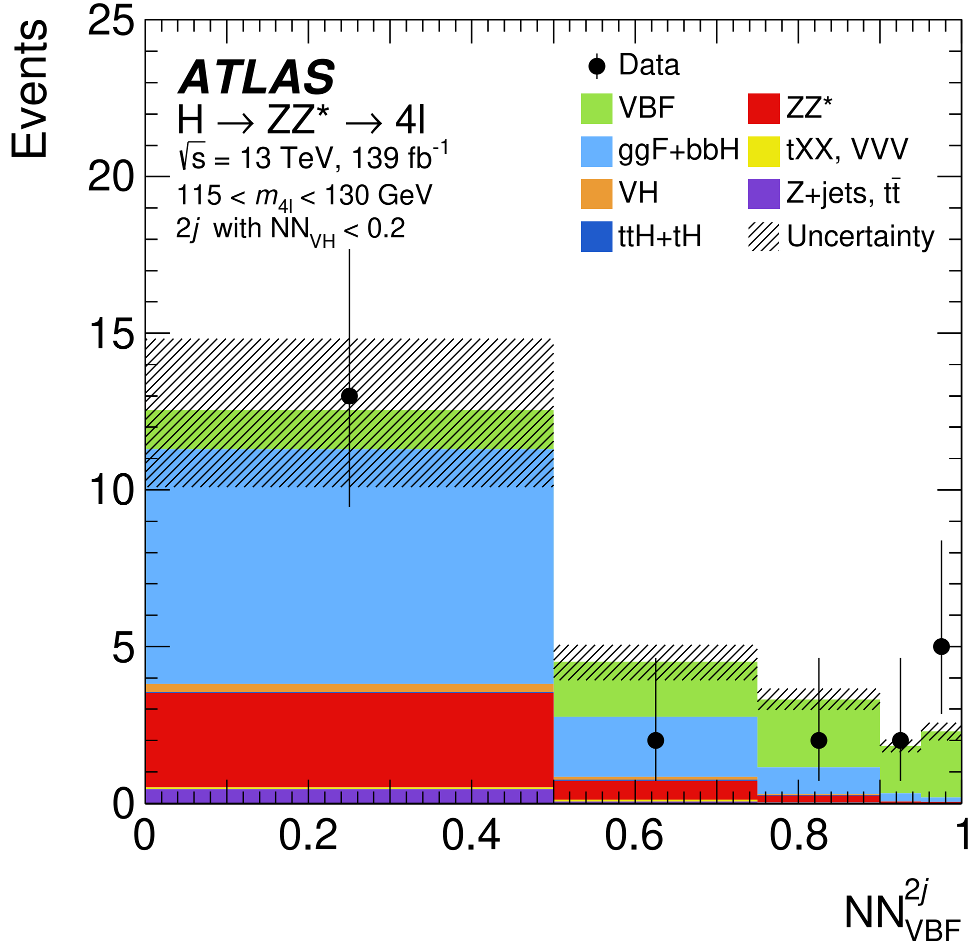
- New full Run 2 results on search for CP-odd Higgs couplings to vector bosons in the Higgs boson to four lepton channel in ATLAS
- Measurement uses optimal observables $\mathcal{OO} = \frac{2\Re\left(\mathcal{M}^{*}_{\mathrm{SM}}\mathcal{M}_{\mathrm{BSM}}\right)}{|\mathcal{M}_{\mathrm{SM}}|^{2}}$
- Limits obtained in both Warsaw and Higgs bases using SMEFT
  - Dominated by interference term, $O(\Lambda^{-2})$ in x-sec, small sensitivity to quadratic terms, $O(\Lambda^{-4})$ in x-sec
    - Implies qualitatively, low expected sensitivity to missing dim-8 operators, also $O(\Lambda^{-4})$ in x-sec
    - => improvement over analyses relying on rates rather than shapes
- Measurements of fiducial differential optimal observables
  - Completing the set for Higgs boson to four lepton
- Also providing fiducial x-sec measurements in VBF phase space

Backup

Category composition



Neural network used to separate VBF from ggF



Expected and observed events per category

	ZZ^* CR	Inclusive SR	VBF-depleted Region	VBF SR1	VBF SR2	VBF SR3	VBF SR4
ggF	8.2 ± 1.3	181 ± 12	165 ± 12	$7.5^{+3.0}_{-2.4}$	$5.6^{+1.8}_{-1.5}$	2.2 ± 0.6	0.49 ± 0.17
bbH	$0.087^{+0.016}_{-0.015}$	1.85 ± 0.05	1.65 ± 0.05	0.11 ± 0.01	$0.072^{+0.010}_{-0.009}$	$0.020^{+0.005}_{-0.003}$	< 0.01
VBF/VH	1.39 ± 0.16	23.8 ± 0.7	13.8 ± 0.6	$1.60^{+0.09}_{-0.08}$	1.89 ± 0.11	3.01 ± 0.18	3.5 ± 0.4
ttH,tH	$0.22^{+0.03}_{-0.04}$	$1.89^{+0.21}_{-0.22}$	0.44 ± 0.05	1.22 ± 0.14	0.179 ± 0.023	$0.046^{+0.009}_{-0.010}$	< 0.01
ttV,VVV	6.79 ± 0.13	1.31 ± 0.06	0.62 ± 0.04	0.53 ± 0.04	0.150 ± 0.020	< 0.01	< 0.01
ZZ^*	229^{+20}_{-25}	98^{+6}_{-9}	92^{+6}_{-8}	$3.5^{+1.3}_{-1.7}$	1.7 ± 0.6	$0.48^{+0.16}_{-0.15}$	$0.086^{+0.025}_{-0.028}$
Zjet,$t\bar{t}$,WZ	21 ± 5	13 ± 4	12 ± 3	0.8 ± 0.9	0.3 ± 0.6	0.07 ± 0.26	0.01 ± 0.09
Total SM	267^{+21}_{-26}	321^{+14}_{-15}	286^{+14}_{-15}	15 ± 3	$9.9^{+2.0}_{-1.7}$	5.9 ± 0.7	4.1 ± 0.5
Data	294	311	276	14	9	4	8

Results: coupling limits for 68% and 95% CL

EFT coupling parameter	Expected 68% CL	Expected 95% CL	Observed 68% CL	Observed 95% CL	Best-fit value	SM p-value	Fit type
$c_{H\widetilde{B}}$	[−0.18, 0.19]	[−0.37, 0.37]	[−0.42, 0.31]	[−0.61, 0.54]	−0.078	0.86	decay
$c_{H\widetilde{W}B}$	[−0.36, 0.36]	[−0.72, 0.72]	[−0.56, 0.53]	[−0.97, 0.98]	−0.017	0.99	decay
$c_{H\widetilde{W}}$	[−0.63, 0.63]	[−1.26, 1.28]	[−0.07, 1.09]	[−0.81, 1.54]	0.60	0.37	comb
$\widetilde{d}$	[−0.009, 0.009]	[−0.018, 0.018]	[−0.017, 0.014]	[−0.026, 0.025]	−0.003	0.86	decay
$\widetilde{c}_{zz}$	[−0.77, 0.79]	[−2.4, 2.4]	[0.37, 1.21]	[−1.20, 1.75]	0.78	0.11	prod
$\widetilde{c}_{z\gamma}$	[−0.47, 0.47]	[−0.76, 0.76]	[−0.54, 0.54]	[−0.84, 0.83]	0.083	0.93	decay
$\widetilde{c}_{\gamma\gamma}$	[−0.38, 0.38]	[−0.76, 0.77]	[−0.52, 0.48]	[−0.99, 0.93]	−0.01	0.99	decay

Effects of including x-sec or CP-even couplings in analysis

- Including only linear terms in morphing:
  - 68% (95%) CL limits change by ~1% (~3%)
- Rather than normalizing each morphing point to SM, scale by the expected SMEFT x-sec:
  - Decay-only limits decrease by < 5% (10%) for 68% (95%) CL
  - Production-only limits ($\tilde{c}_{ZZ}$) tighten by 10% (50%)
- Checked including non-zero CP-even couplings for c_{HB}, c_{HWB} and c_{HW}
  - For current experimental limits on CP-even coupliings:
    - Negligible effect for production-only
    - Weaker limits for decay-only at ~1%